# HANDBOOK ON
# MEASUREMENT OF SOIL MOISTURE
# BY THE NEUTRON SCATTERING METHOD

A Compilation of Available
Information for Use Within
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# HANDBOOK ON MEASUREMENT OF SOIL MOISTURE BY THE NEUTRON SCATTERING METHOD

## Contents

## FOREWORD

This handbook has been prepared as an operational guide for use of research personnel to whom the neutron-scattering method of soil moisture measurement is new. It brings together recommended procedures based upon approximately 6 years of research and testing by a number of scientists operating in a nationwide diversity of soil and climatic conditions. It is intended as an interim paper with restricted distribution. If there is sufficient demand, it will be revised at a later date into a Forest Service category II handbook for more widespread distribution. This paper is concerned with depth measurement of soil moisture only. Surface soil moisture and soil density measurements are not dealt with because experience in the use of the instruments is insufficient to provide a basis for sound recommendations of operation.

This handbook, written by James Douglass of the Southeastern Forest Experiment Station, is one of the results of a Forest Service work conference held at the Coweeta Hydrologic Laboratory in August 1961. This conference was called to bring together current knowledge on the neutron-scattering method of measuring soil moisture. Other Forest Service research personnel who attended the meeting and contributed their knowledge to the subject were: Dr. Paul Koshi, Tempe, Arizona; Mr. Robert Merriam, Provo, Utah; Mr. Harold Herring, Wenatchee, Washington; Mr. Richard Marston, Columbus, Ohio; Mr. Willie Curtis, La Crosse, Wisc.; Mr. John Thames, Oxford., Miss.; Mr. James Douglass, Union, South Carolina; and Dr. John Hewlett, Franklin, N. C.

Acknowledgment is also made of the significant contributions of Dr. Roger McHenry and Mr. Paul Nixon of the ARS laboratories at Oxford, Miss., and Lompoc, Calif., respectively, and of Dr. Kenneth Knoerr, School of Forestry, Duke University.

## APPRAISAL OF METHODS OF MEASURING SOIL MOISTURE

2.1 - Measurement Methods. The three most commonly used methods of measuring soil moisture are gravimetric, electrical resistance, and neutron scattering methods. Each has its desirable features and its limitations. The best method is dictated by the nature of the research project.

2.11 - Gravimetric Method. The gravimetric method involves extracting a soil sample, determining its moist and oven-dry weight and expressing weight of water lost through drying as a percent of the ovendry weight of soil. Moisture content in percent by weight is an expression commonly used, but if moisture is expressed on a volume basis the percentage must be corrected for density. Sampling equipment and field and laboratory procedures applicable to the gravimetric method are described elsewhere (12, 15).

Desirable features of the method include the following:

1. Equipment is relatively inexpensive. A modest but complete set of field and laboratory equipment can be purchased for about $200.

2. Moisture content is determined directly from soil samples.

3. Sampling depth can be accurately controlled permitting separation of data into strata of any desired depth.

The method has undesirable features:

1. Sampling destroys the site, injures vegetation, and interferes with natural soil moisture dynamics.

2. The method is laborious and time consuming limiting the number of samples possible within time available for sampling.

3. Some soils are difficult to sample. Dry single-grained soils are difficult to remove from the sampling hole. Water draining into sample holes in very wet soils often contaminates deeper samples.

4. Practical considerations limit the depth of sampling, usually to about four feet.

5. The sample of soil is usually small.

6. The error of the method is large and difficult to calculate because soil density and moisture volume are usually calculated from different samples.

2.12 - Resistance Method. The electrical resistance method is a widely used method of measuring field moisture in situ. It employs the principle that resistance to passage of an electrical current between two

# HANDBOOK ON MEASUREMENT OF SOIL MOISTURE BY THE NEUTRON SCATTERING METHOD

1.1 - Introduction. The neutron scattering method of measuring soil moisture is proving to be efficient and useful for studying soil moisture content *in situ*. It has application in a wide variety of soil and water research and, within its limitations, is an effective measurement tool. Its application is not universal and in some studies other methods may be preferred. Evaluation of the relative merits of a measurement method and the manner of using it in the field will depend largely on requirements and physical conditions of the research to be done. One objective of this handbook is to present advantages and limitations of several methods of measuring field moisture content as a basis for selecting the most suitable method for a particular study.

Other methods of measuring soil moisture content have been discussed, evaluated and recorded elsewhere, but the neutron method is new and while theoretical aspects have been widely discussed in the literature, little information is available on using the method to obtain field moisture. This handbook brings together widely scattered sources of information and experience on field use of neutron equipment which can be used as guides for efficient use of the neutron method in soil moisture research work.

Water in soil is commonly expressed as a percentage of a volume of soil, but in order for this expression to have meaning it must be related to some known standard such as wilting point or saturation or to a second observation of soil moisture made at another point in time. Textural makeup, a highly variable factor, is very significant in soil moisture studies. For instance, a clay soil may contain 20 percent moisture at wilting point, but a sand may have only 2 percent moisture. Therefore, it is highly desirable to obtain data on wilting point, saturation and/or field capacity.

In studies where information is desired on the amount of moisture available to plants, storage capacity of soils, moisture use by vegetation, amounts or rates of evaporation etc., meaningful soil moisture data are usually obtained only through repeat measurements of moisture.

electrodes buried in the soil varies inversely with moisture content. Usually the two electrodes (soil units) are imbedded in fiberglas, nylon, or fiberglas gypsum and attached to an ohmmeter or modified Wheatstone bridge to measure resistance. The soil units are gravimetrically calibrated in the laboratory or field (12, 15), to indicate moisture volume.

Advantages of the resistance method include:

1. Site is preserved, and the same soil mass can be remeasured.

2. Abrupt transitions in the soil moisture profile can be detected if enough soil units are used.

3. Soil units usually remain serviceable for several years.

4. Field measurements can be made more rapidly than by any other method and are reproducible.

Weaknesses of the resistance method include:

1. Calibration of each soil unit is laborious and time consuming and limits the opportunity to replicate measurement locations.

2. Equipment is relatively expensive. Soil units cost from $1 to $5 depending on the type used, and the ohmmeter or modified Wheatstone bridge costs about $200.

3. Errors from many sources reduce reliability of moisture estimates. Soil units are sensitive to temperature fluctuations and salt concentrations and are less reliable in very wet and dry soils. Deviations due to wetting and drying (hysteresis) and shrinkage of soil away from the unit also introduce error.

4. Failure of soil units terminates a continuous record. If units are replaced, the site is modified and no longer comparable. If they are not replaced, no more data from that depth and location are obtainable.

5. Time and physical considerations limit the soil depth measured. Depth limitations are similar to gravimetric sampling.

6. Moisture condition between soil unit depths must be interpolated.

2.13 - Neutron Scattering Method. This method is based on physical laws governing the scattering of neutrons in matter (1, 4, 22). Briefly, the equipment is designed to measure the density of a cloud of slow neutrons in a soil mass, the slow neutron density being related to moisture volume of a soil.

When a source of fast neutrons is placed in the soil, the fast neutrons emitted collide with nuclei of the soil. The collision reduces the speed of the neutron and changes its direction of movement (thus the name--neutron scattering). This slowing down (moderating) process continues until the neutron no longer loses energy. Thereafter, slow neutrons are scattered in accordance with theories of gaseous diffusion until they are absorbed by other nuclei.

Hydrogen is the most efficient moderator of neutrons because (1) the energy loss is greater in a collision with a hydrogen nucleus and (2) the probability of a collision is greater for hydrogen than for any other element. Hydrogen, being present in water, is also the most abundant neutron moderator in soil; thus the density of slow neutrons surrounding a fast neutron source is related to the hydrogen volume of the soil. The neutron method of measuring soil moisture utilizes equipment designed to measure the density of a cloud of slow neutrons in a soil mass, the slow neutron density being related to the volume of water in the soil.

In measuring soil moisture, slow neutron density is measured by a detector tube filled with a gaseous neutron absorber. When a slow neutron is absorbed by the gas, an alpha particle is produced and the impulse is transmitted to a counter or scaler where it is recorded.

Complete sampling equipment (figure 2.13) consists of a probe which contains both the source of fast neutrons and the detector tube and a scaler which records the number of slow neutrons detected during a given time interval. Impulses from the detector tube are amplified in the preamplifier and transmitted to the scaler through the connecting cable.

Advantages of the neutron method are similar to those of the resistance method.

1. The counting rate is converted directly to moisture volume eliminating the need for separate measurement of soil density and moisture weight.

2. Access tube installation is nondestructive and the same soil mass can be measured repeatedly.

3. Field measurements are relatively rapid. Measurement time is intermediate between that for gravimetric and resistance methods.

4. Larger volume of soil is measured than by other methods and theoretically more representative of moisture conditions.

5. Deeper depths can be measured than by other methods.

6. Calibration curves for probes are applicable to a variety of soils (see 4.3 for a fuller discussion).

Disadvantages of the neutron method:

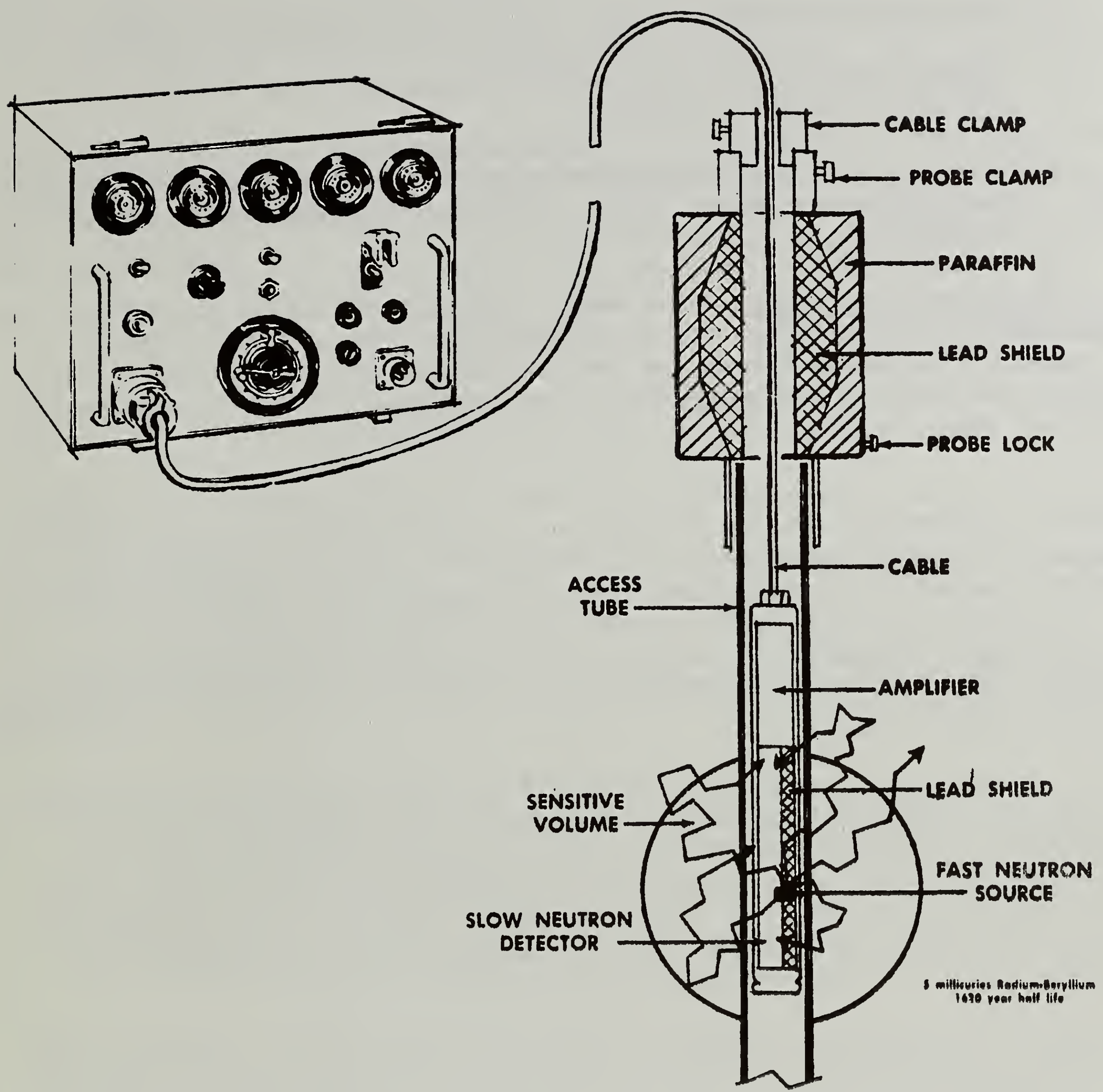



Figure 2.13. Diagram of nuclear soil moisture equipment. The probe is shown extended into the access tube. (Photograph courtesy Nuclear-Chicago Corporation)

1. Equipment is costly. Cost of the probe and scaler is about $2700. However, with large volumes of data, cost per measurement may be lower than for other methods.

2. Frequent instrument failure causes interruption of records.

3. Separate calibration of surface foot is required because of soil-air interface effects.

4. Depth of discrimination between soil layers without overlapping measurements is about 12 to 36 inches depending on moisture conditions.

<u>2.2 - Precision of Methods</u>. Advantages and limitations of available methods may not be decisive and a choice may be made on the basis of the precision of the moisture estimates. In such an evaluation, two types of measurement errors should be considered--calibration error and field measurement error.

Calibration error is associated with predicting one variable from another and is a measure of the size of the error expected from a <u>single</u> moisture observation. Calibration error for resistance units is reported to be about 0.5 percent by volume for moisture contents below field capacity and about 1.0 percent by volume for moisture contents above field capacity (<u>12</u>). Calibration error for the neutron method is less than 1 percent (<u>17</u>, <u>19</u>, <u>22</u>, <u>23</u>) and is reported to be less than that of the resistance method (<u>17</u>).

If more than one measurement is taken at the same location, the calibration error is constant and becomes inoperative and does not enter into comparisons of precision of field measurements by different methods. Therefore, the error to be considered in comparing methods is the error of the estimate of change in field moisture. This error is a composite error arising from variations in soil, moisture, site, instrument performance, and all other sources except calibration error.

The error of estimate of changes in field moisture can be reduced by the covariance associated with repeat measurements at a particular location. This applies to both neutron and resistance measurements, but the time-consuming process of calibrating and installing resistance units limits replication of measurement locations. Consequently the field measurement error of resistance measurements will usually be greater than the error of neutron measurements. Also, the possibility of difficulties arising from the presence of salts, temperature, hysteresis, and the smaller measured volume of soil discourages use of the resistance method.

Gravimetric sampling involves two variables--percent moisture by weight and soil density, and their interaction (<u>8</u>). Even when the interaction is included, the sampling error remains larger than that of neutron measurements. In one area, comparisons of sampling intensity required for a specific standard error of moisture by gravimetric and neutron methods showed that one neutron measurement was equivalent to about 7 gravimetric samples (20).

Special requirements imposed by the study may favor the gravimetric over the neutron method. In addition to the examples previously cited, if measurement of the soil profile were needed only twice yearly to estimate water storage potential of the soil, the gravimetric method could give equally precise measurements if more samples were collected, but at a substantially lower cost. Thus there remain situations when resistance or gravimetric methods might be favored over the neutron method.

2.3 - Selection of a Measurement Method. Careful study of the objectives of a moisture study will define parameters to be measured, precision needed, and will often prescribe the method or methods which can be used. In some instances, joint use of two methods might be considered to offset disadvantages of either method. An example is measurement of the surface foot by gravimetric or resistance methods and measurement of lower depths by the neutron method. Also, the needs of some studies may go beyond simple measurement of moisture and other techniques such as tensiometers, to provide data on tension relationships, should be used. Fulfillment of the objectives of the study within the limits of time and funds imposed will determine the choice to be made.

In conclusion, field measurement error for depths other than the surface foot of soil will usually be smaller for the neutron method than for other methods. However, if detection of abrupt transitions in moisture, separation of the profile into small depth intervals or into soil horizons, sampling only the upper foot or two of soil, or infrequent sampling is needed to fulfill study objectives, resistance or gravimetric may be more efficient.

## USE OF NEUTRON-SCATTERING EQUIPMENT

3.1 - Equipment Available. Equipment employing the neutron theory is currently offered by Nuclear-Chicago Corporation, Des Plaines, Ill., and Troxler Laboratories, Raleigh, N. C. (figure 3.1). Both makes of equipment will effectively measure moisture content and there appears to be no significant difference in their performance. They differ somewhat in design, and under peculiar conditions one system may be better adapted than the other. Some characteristics of probes and scalers which may be of interest in selection of equipment are described below.

The 5-millicurie source in the 1.50" diameter Nuclear-Chicago probe is locked securely in place as a safety feature to prevent its being removed. The 2-millicurie source in the 1.865" diameter Troxler probe is easily removed so that one source may be used in the surface moisture probe and the depth moisture probe. While frequent changing of the source is not recommended, from a safety standpoint, Troxler officials claim that very infrequent changing is not a safety hazard. The different source strength has no effect on vertical sensitivity of the probe.

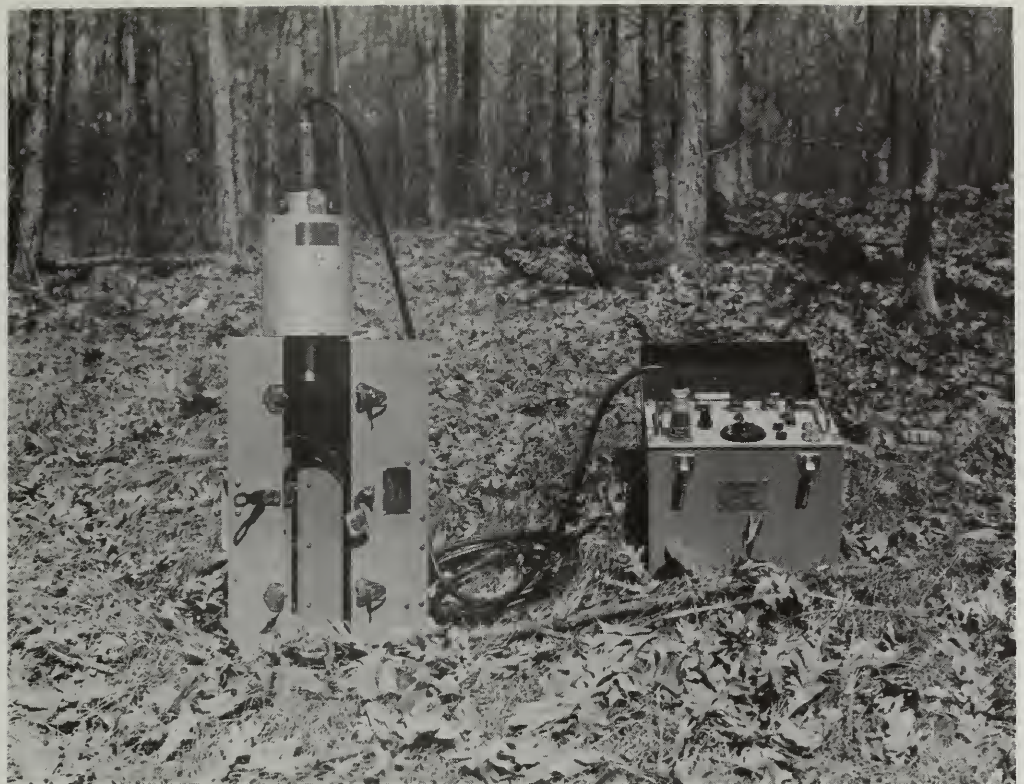
Van Bavel (22) reported a more linear calibration curve with a source located at the mid-length of the detector tube (Nuclear-Chicago). The overall counting rate was somewhat less, however, than that obtained with the source located at the end of the detector tube (Troxler). He concluded that the end positioning gave greater counting efficiency per millicurie Ra-Be and better shielding than center positioning but at the expense of the linearity of the calibration curve. Positioning of the source has little effect on resolution.

The Nuclear-Chicago probe weighs approximately 32 pounds in its shield and costs about $1385 in contrast to a weight of 30 pounds and cost of $1000 for the Troxler probe.

The Troxler scaler contains nine separate modules (packaged circuits) which are removable and make repairs relatively simple and rapid. Module replacement can be made at the factory, or stations can purchase spare modules for replacement by the operator. Several of these modules are identical so that only 4 or 5 need to be kept for replacement. These cost about $400.00. Troxler has a trade-in policy so that future replacements cost somewhat less than this. Nuclear-Chicago is not modular constructed and it is necessary to return the scaler to the factory. This often results in gaps in the collection of soil moisture data and delay in research progress.

The Nuclear-Chicago scaler has a cover over the face of the instrument, protecting the decade glow tubes and other controls. The Troxler scaler has no protective cover.

The timer on the Troxler scaler is mechanical with a one-minute preset counting time while the Nuclear-Chicago timer is electrical and can be preset for either one or two minutes counting time. Both timers apparently give satisfactory service on current model scalers. Nuclear-Chicago uses a longlife leakproof wet cell battery and Troxler a nickel-cadmium



A

B


C

Figure 3.1. Nuclear-Chicago probe and scaler (A). Troxler scaler (B), and probe (c).

dry cell. Both are rechargeable, the Nuclear-Chicago from a built-in charger and the Troxler from a separate charger. The Nuclear-Chicago scaler weighs 33 pounds in contrast to only 15 pounds for the Troxler. The built-in charger in the Nuclear-Chicago accounts for this difference. Built into the Troxler is a rate meter which can be used for quick measurements or comparisons and also to read the battery voltage and to check the high voltage operating level. The Nuclear-Chicago scaler does not contain a rate meter.

Approximate cost of the Troxler scaler, including the separate battery charger, is $1,740; Nuclear-Chicago costs approximately $1,385.

<u>3.2 - Health Considerations</u>. Use of radioactive materials by research agencies of the U. S. Department of Agriculture is regulated by the Radiation Safety Committee, and rules governing use of radioactive sealed sources are contained in Section 6 of the Radiation Safety Handbook (<u>21</u>). Radiation Safety Committee approval is required prior to purchase of soil moisture probes[1/], and Departmental requirements, covered in detail in the Radiation Safety Handbook, must be followed. All radioactive substances are potential health hazards regardless of the level of radiation and appropriate precautions must be taken to avoid overexposure. Elaborate safety precautions are mandatory for protection of personnel, but if handbook regulations and commonsense rules for safe handling of equipment are followed by personnel, there is little danger of overexposure to radiation. The maximum permissible weekly dose of radiation is 300 milliroentgens (mr) per week. This exposure will not be approached unless safety precautions are flagrantly violated, since exposure under normal working conditions is under 5 mr/week. Exposure is recorded by film badges which must be worn by the operator.

Greatest exposure to radiation occurs from working near the source. Radiation from a 5 millicurie (mc) source exceeds 50 mr/hr at the surface of the shield (which is designed to reduce the radiation hazard). The level drops rapidly as distance from the source increases; thus an important rule of safety is to maintain maximum distance between operator and source. Carrying the probe in its shield, subjects the operator to some radiation, but appropriate carrying devices (figure 3.4) which maintain maximum distance between operator and source minimize radiation. Furthermore, total carrying time is small in normal field operations and the source is in the soil most of the time. Once the source is below 12 inches, the radiation level is low and for deeper depths, it is negligible.

Semiannually the probe must be tested for radiation leakage. The semiannual leak testing causes more problems than all other regulations, especially if returning the probe to the factory interrupts continuity of records. With approval of the Radiation Safety Committee, leak tests can be made at field installations provided a detection device is available capable of detecting radiation of 0.005 microcuries strength.

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1/ Correspondence should be directed to the Radiation Safety Officer, Radiation Safety Committee, Plant Industry Station, Beltsville, Md.

3.3 - Equipment Tests. Equipment should be checked for operation defects when it is received. Operating instruction and maintenance manuals are furnished with instruments by the manufacturer. After equipment is received, it should be visually inspected for shipment damage and checked for functional defects. Experience indicates that equipment will usually be functioning properly or will not function at all. Scalers contain a built-in system but probes do not. To test the entire system, attach probe to scaler and accumulate 5 to 10 one-minute slow neutron counts with probe in the shield (shield counts). The system is functioning properly if, 19 times out of 20, the shield count does not vary from the rated count, as determined by the manufacturer, by more than twice the square root of the shield count (theoretical error of radiocounting).

3.31 - Timer. Reproducibility of the timers on scalers should be verified. Both scaler timers are precision rated at 0.1 percent error or less, but this may vary and should be checked periodically (see instruction manual). If precision is less than that obtainable by stopwatch timing, replace or repair the timer or use an accurate stopwatch. Careful timing should contribute no more than 0.1 to 0.2 percent to the error of the recorded counts.

3.32 - Battery. The wet battery should be checked daily for leakage, electrolite level, and charge by appropriate test measures for the particular type of battery used. Nuclear-Chicago equipment provides a battery test light (not completely reliable) and floating beads for testing electrolite level and charge. Both the wet and dry battery should be recharged after each period of use, and proper battery charge can be assured if the battery charger is connected after taking measurements and left connected until the next use period. The charging circuit has a built-in safety device to prevent damage by overcharging.

3.33 - Detector Tube Voltage. Each detector tube has a proper operating voltage range (plateau) which is determined by the factory. The plateau should be verified after equipment is received, after repairs to the probe, and each 6 months thereafter. The plateau ranges about 50 volts above the knee of the counts vs. operating voltage curve (figure 3.33). The counting rate will be stable for any plateau voltages, but for maximum detector tube life operating voltage should be set about 50 volts above the lowest plateau voltage.

If the plateau shifts but counting rate is unchanged, the high voltage indicator should be reset for proper voltage. If counting rate changes proportionally at all moisture contents (determined by counts in shield, water drum, and standards), counts are corrected by the count-ratio method. (Count-ratio is the counting-rate in soil over counting-rate in shield, and count-ratio rather than direct count is used to compute moisture.) If counting-rate change is not proportional at all moisture levels, the instrument must be recalibrated or returned to the manufacturer for repair.

3.34 - Shield Counts. Shield counts provide one check on functioning of equipment. They can be made in the field, but in hot environments counts will decrease as the temperature of the shield increases (16). Improvements

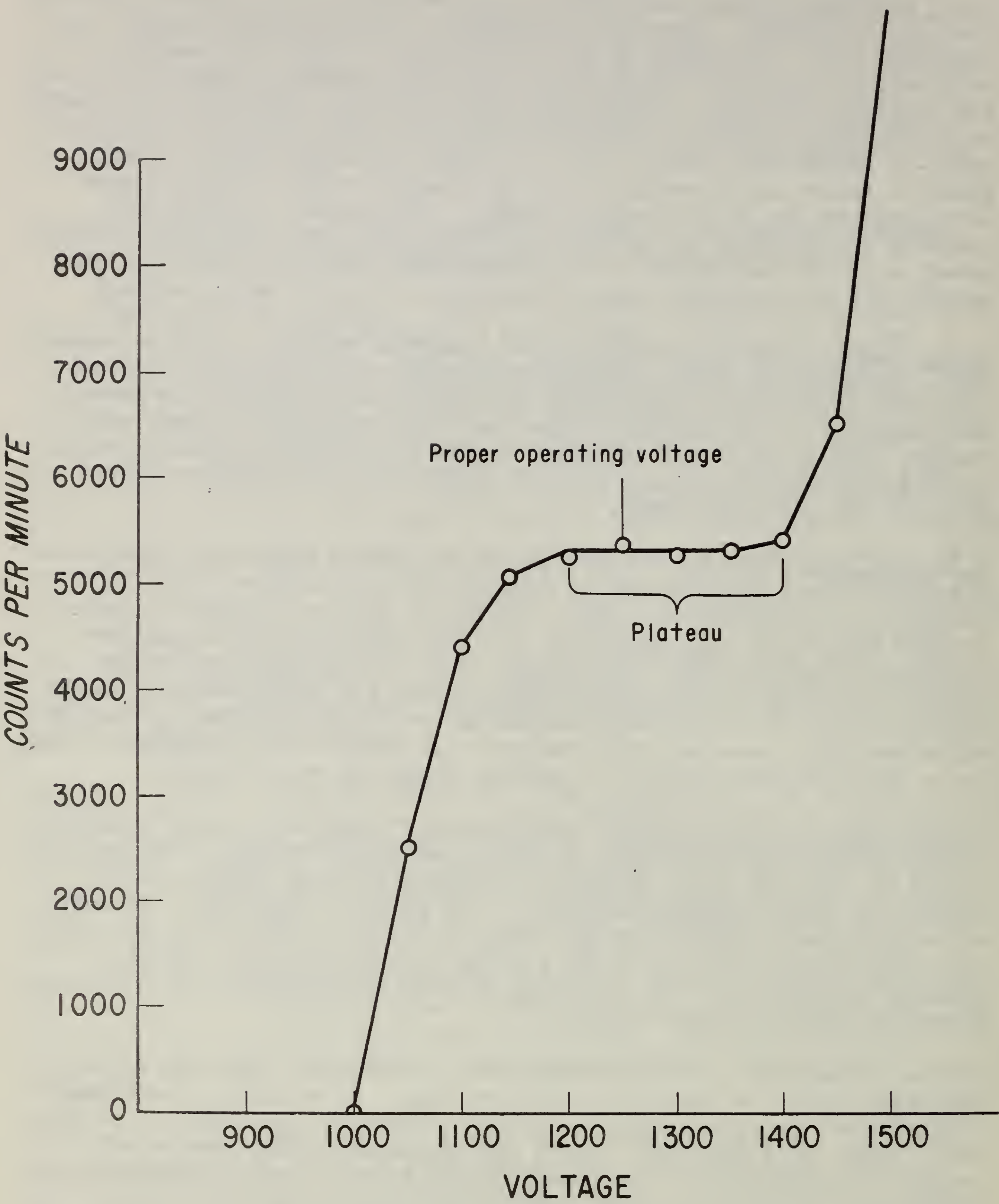


Figure 3.33. Plateau for a P-19 moisture probe showing proper operating voltage.

in equipment have reduced this effect but counts under constant temperature conditions are recommended. The number and frequency of shield counts needed is debatable and depends somewhat on operator experience, but twice daily shield counts made before and after operation under constant temperature conditions are sufficient if equipment is functioning properly. Daily shield counts on graph paper aid in detecting gradual shifts in counting rate and provide a long-term, continuous record of instrument performance.

Field plotting of measurements of moisture on graph paper should also be standard procedure as a means of checking instrument performance against expected trends in moisture levels based on weather conditions. Peculiar counts can be rechecked immediately and supplementary shield counts can be made in the field as necessary to verify proper equipment functioning.

The same timing interval should be used for both shield counts and field measurements so that changes in the counting-rate can be corrected by the count-ratio method. Five to 10 shield counts should be taken each time shield counts are made; fewer counts may by chance all be high or low, and not give a true indication of actual counting-rate.

<u>3.35 - Depth Referencing of the Probe</u>. Depth markings on the probe cable should be checked and corrected if necessary. To reference a probe, take one-minute counts by one-inch depths as the probe passes through an access tube welded in a sheet metal pan or bucket containing a 2- to 4-inch deep layer of water (figure 3.35). Highest counts will be obtained when the center of the radioactive source in the probe is at the middepth of the water. Position the probe so that the center of the radioactive source is in the center of the water and measure the distance between the center of the water and the depth reference index (w). Then subtract the height of the shield (x) plus access tube (y) from the vertical distance w to determine the depth of the source center (z) below the ground surface. For example, if w = 25", x = 12, y = 6, z must be 7. If the cable marking at the index is 10, the cable reference is 3 inches in error and the 10 represents a soil depth of 7 inches. This 3-inch difference must be kept in mind when using the probe. If the cable does not have depth markings, this procedure can be used to mark the cable.

<u>3.36 - Verifying Manufacturers' Calibration</u>. Validity of the manufacturers' calibration curve should be verified for soils where field measurements will be made. The manufacturers' curve is valid for many soils (<u>13</u>), but in other soils, it may not apply (<u>16</u>). Verification is accomplished by comparing gravimetrically determined moisture volume with moisture volume determined by using the manufacturers' curve. The curve should be checked at a minimum of four moisture contents preferably covering a moisture range of 20 percent moisture by volume (example: verify the curve at 15, 20, 30, and 40 percent moisture). Procedures for verifying the calibration are described in Section 4.3, Calibration of Probes.

If the slopes of the two curves differ significantly, complete recalibration is necessary. If the slope is correct and only levels differ, curve level can be adjusted by shifting the curve until counting-rates or count-ratios represent the correct moisture content.

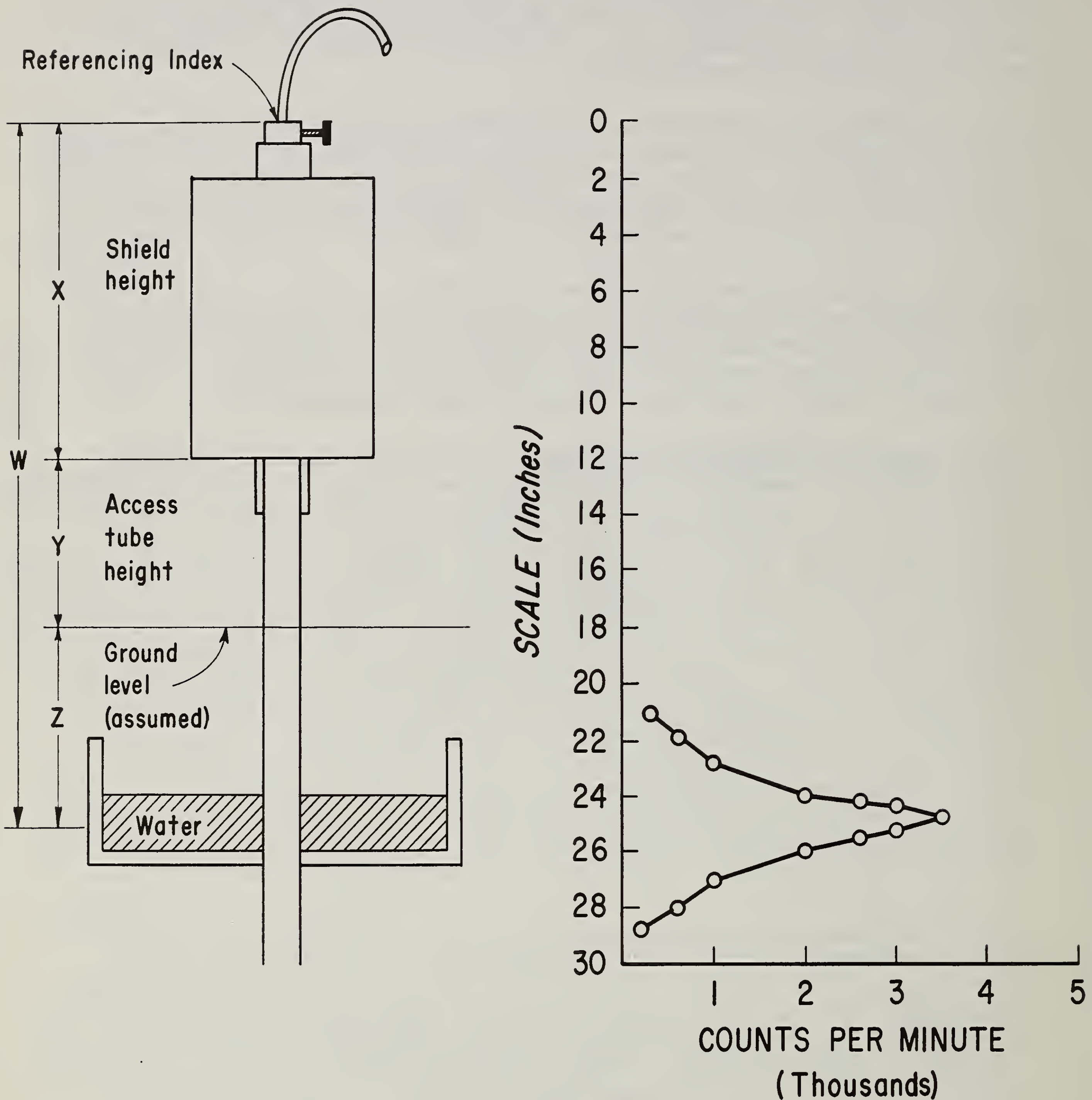


Figure 3.35. Diagram of a method of referencing the probe cable for depth measurements.

3.4 - Site Protection. Neutron measuring equipment permits nondestructive moisture measurement, but adequate measures must be taken to protect the site during operations. Grasses and shrubs can be trampled, litter destroyed or moved, and soil compacted until moisture conditions no longer represent original conditions. Damage is usually greatest near access tube sites although trails may interfere with normal moisture patterns throughout the study area. Simple site protection devices (figure 3.4) can prevent much of this damage and should be used, particularly when frequent and prolonged measurements are contemplated.

In row crops and wildland research, site protection and transporting devices might be combined. In some cases simple wooden platforms carried from site to site may suffice. Since repeated travel over the same trails may change site characteristics, random routes to tubes are desirable where possible.

3.5 - Transportation of Equipment. Although portable, neutron scattering equipment is heavy and some device for transporting it between locations is desirable. Transporting vehicles can be built according to individual ingenuity and needs (figure 3.4). Factors to consider when developing a method of conveyance include cushioning equipment against shock, stability, terrain, radiation safety hazard, weight (loading and unloading from vehicles), ruggedness, and climatic conditions.

3.6 - General Considerations. When cold, electronic equipment may perform erratically. A 5- to 10-minute warmup should be allowed prior to taking counts. Since warmup is desirable after each break in measurements, equipment should be operated continuously until field measurements are finished. During lunch periods or other breaks, the probe can be left underground in the access tube to maintain a more uniform operating temperature and to decrease radiation hazards.

Equipment should not be used around hydrogenous material, desk calculators, other radioactive materials, vehicle engine, and other extraneous interference which causes erratic counting.

The cable connecting probe and scaler may stretch, causing depth positioning errors. These may be eliminated by fastening a chain to the top of the probe as an aid to positioning it.

Errors of measurement can be detected and corrected at the time of observation if data sheets for the previous measurement are carried to the field or if data are computed and plotted on graph paper between measurements. Conversion to percent moisture from counts or count-ratio is facilitated by preparing a conversion table or slide rule for quick computation. This procedure works well for measurement timing intervals of one minute or longer, but conversion may increase field measurement time if shorter counting times are used.

If large quantities of data are expected, data processing equipment can be used to convert counts or count-ratios to moisture and to summarize data in any manner desired. If moisture is computed after field measurements and if moisture changes with time rather than absolute quantities

Figure 3.4. Wheelbarrow cushioned with sponge rubber for transporting soil moisture equipment. Platform under operator protects site from undue disturbance.

of moisture are desired, the "a" factor in the prediction equation $y = a + bx$ can be dropped since it is a constant (where y is percent moisture by volume and x is the counting-rate or count-ratio). Computation reduces to $y = bx$ and if inches of water is desired, moisture is then determined by $y = bx$ (soil depth).

Mechanical failures sometimes occur causing interruption of measurements at vital times during studies. Minor failure can often be corrected if a small supply of spare parts, especially detector tubes, transistors, and preamplifiers for probes and switches, fuses and modules (Troxler) for scalers are stocked at field stations. Because of the specailized nature of the equipment, component failure usually cannot be diagnosed at local radio-TV shops since they are not equipped with proper testing equipment and specailized components--resistors, transistors, capacitors, modules, etc.--needed for repair. If failure occurs, other than a cable break, which cannot be corrected by replacing the parts listed above, equipment should be returned to the manufacturer or his authorized service representative.

Equipment down time for Nuclear-Chicago equipment returned to the factory has varied in the past from a week to about 3 months. Information on down time of the Troxler probe is limited, but experience to date has shown that down time is about one week because the manufacturer has furnished replacement equipment by air freight (on loan) when lengthy repairs were contemplated.

Repair and modification of equipment to incorporate design changes should be budgeted. A planning figure of $250 yearly is suggested for work of this type.

# INSTALLATION OF ACCESS TUBES AND CALIBRATION OF PROBES

4.1 - Types of Access Tubes. Various kinds of pipe are used for access tubes. Each type requires separate calibration because counting-rate varies with diameter, wall thickness, and composition of tubing. Coatings and certain mineral composition used in manufacture can adversely affect moisture measurement, and even the same type tubing may vary if quality control measures are lacking or are unreliable. Since accuracy of results might be jeopardized by using improper tubing, and since probes may need to be used at several field installations, access tubing should be standard whenever possible.

The Troxler probe is factory calibrated in seamless aluminum tubing (ASTM #6061-T6, 2-inch OD with .035-inch wall thickness). This tubing is recommended for field calibration and installation. It is lightweight, rust resistant, economical and is readily available in 12-foot lengths. Lengths over 12 feet can be made by joining pipe with flush couplings. However, aluminum tubing should not be used in alkaline soils and it may bend if driven into soil. If aluminum cannot be used, an alternate tubing (cold drawn seamless steel, MT 1015 or 1012 medium hard, 1.555 inches ID and 1.625 inches OD for the Nuclear-Chicago probe and 1.900 inches ID minimum for the Troxler probe) is recommended. It is more expensive and subject to corrosion but is available in random lengths up to 21 feet. Factory calibration of the Nuclear-Chicago probe is made with this tubing.

4.2 - Installation of Tubing. Ideally, access tubing should be placed in a snug-fitting, predrilled hole. Since ideal placement is not often achieved because of soil conditions, three general methods of installing tubes have evolved. In order of desirability, they are (1) the auger method, (2) the hand driving method, and (3) the machine drilling method.

4.21 - The Auger Method. This method can be used in medium to light textured rock-free soil. At the desired tube location, remove litter and predrill a vertical hole to the desired depth with a $1\frac{1}{2}$-inch or 2-inch diameter soil auger. Soil can be saved for laboratory analysis if desired. During augering, stand on platforms to prevent trampling areas adjacent to the access tube. Check the inside of the access tube for dents which might interfere with probe movement with a probe length, machined steel slug about .002 inch larger in diameter than the probe. Remove dents by driving the slug through the tube. A shouldered, shaped hardwood plug (figure 4.21) inserted in the bottom of the tube will seal the tube and guide it into the auger hole. This plug also prevents edges of the pipe from shaving soil from the side of the hole, thereby minimizing air space between soil and tube. Use a shaped driving head to prevent bending the tube if it must be driven into the soil.

After the tube is installed, cut to the desired height above the ground (if not precut) and cover with a painted, numbered can. The can and access tube accumulate heat which has a moderating influence on soil temperature (6). The interior of the can may be insulated to minimize heat exchange and to lessen condensation inside the tube.

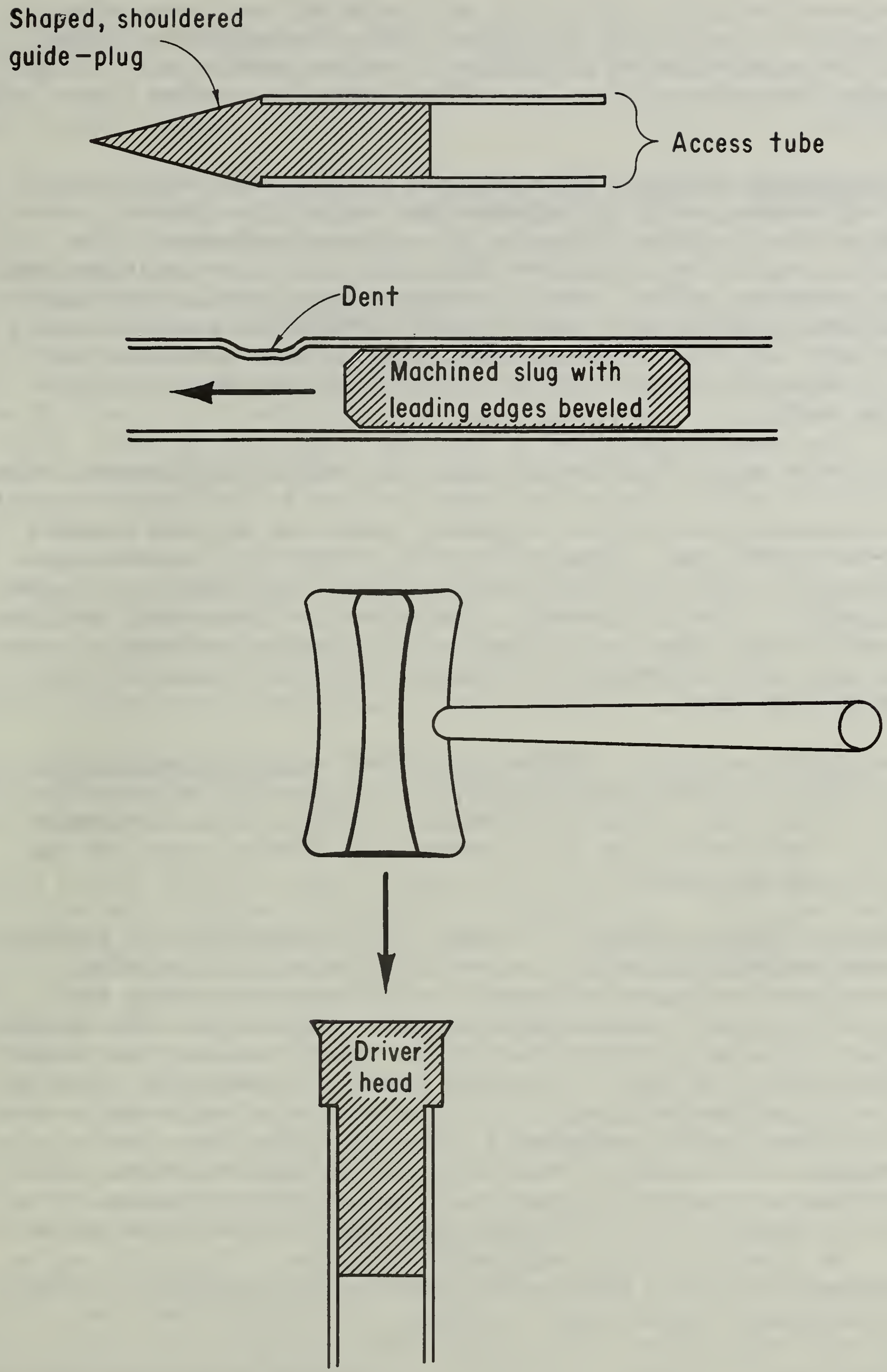


Figure 4.21. Diagram of access tube guide-plug, machined slug, and driver head used in installing and checking access tubes.

An alternate method is to auger from the inside of the access tube pushing the tube down as soil is removed. The disadvantage of this method is that several tubes of different lengths must be used if the hole is over 4 feet deep. This may enlarge the hole causing a poor soil-tube junction.

4.22 - Hand Driving Method. Fine textured soils which exhibit strong swelling tendencies, and dry, single-grained soils offer special problems. Clays often swell against the tube preventing downward tube movement in a predrilled or augered hole. Borings from single-grained, dry soils (sands and silts) cannot be removed from the hole because it will not cling to the auger. Both of these situations require driving the tubing into the soil. Tubes 4 feet long are most convenient for driving. Graduations on the tube at one-foot depth intervals aid in determining depth.

The hole is made by driving the tube into the soil 2 to 10 inches. The tube is then removed. In order to twist the tube to facilitate removal, predrill a $\frac{1}{2}$-inch hole through the pipe 4" below the top and insert a 12- to 16-inch steel rod. Extract the soil inside the tube and carefully reinsert the tube into the hole to continue the drilling process until the desired depth is reached. Check the tube for dents, seal the bottom, position the tube in the hole, cut to the desired height, and cap with a can. Twenty feet of tube can be driven by 2 men in 1 to 3 hours by this method.

Since this method produces a slightly oversized hole, the soil-tube interface must be sealed by tamping soil around the tube with a pipe which will fit over the outside of the access tube. This disturbance is admittedly undesirable but it is better than leaving space for the vertical flow of rain water.

4.23 - Machine Drilling Method. If there is considerable rock in the profile, machine drilling may be necessary, although all portable drilling machines have disadvantages. Preliminary tests using the Minuteman drill rig are somewhat encouraging. With augers this machine will drill rapidly through rock-free soils, but in wet clays or stoney soils compressed air or water, depending upon soil conditions, must be used as the jetting medium. Water is not entirely satisfactory because unnatural moisture conditions prevail around the hole for a period of time after tube installation. Both water and air may cause oversized holes which require backfilling to close the soil-tube air space. The drill must be well guided to drill straight holes so the tubes can be inserted. The Minuteman has a good guidance system. The drill can be moved around on its wheels but the rig is heavy and difficult to handle on rough terrain.

4.3 - Calibration of Probes. Calibration curves for probes are supplied by the manufacturer. Much of the early literature supported the manufacturers' view that one calibration curve fitted all soils except those containing unusually large amounts of neutron absorbers or moderators in the form of salt or other minerals (1, 5, 9-11, 18, 22). But as experience with neutron equipment grew, evidence accumulated indicating that

one curve may not work for all soils (16, 9, 3). However, the data are conflicting and indicate the many questions of calibration are not yet settled or fully understood. The influences of bound (adsorbed) water and of other neutron absorbers and moderators than hydrogen in soils are not well known.

The neutron count of a soil is an integrated result of the number of neutrons slowed by collisions with hydrogen in (gravimetrically determined) water, adsorbed (bound) water, organic matter, OH in the crystal lattice, and probably other soil elements, less the number of slow neutrons absorbed by elements such as lithium, boron, chlorine, cadmium, etc. Variation in any of these except the volume of gravimetrically determined moisture affects the calibration curve. Since these substances vary with soils, the concept of field calibration with curves derived from different soil materials has been questioned. Such questioning may be valid since it has been found that calibration of each depth separately improved correlation between moisture content and neutron count (17).

The "best" calibration procedure probably has yet to be devised and of the many methods tested (2), only two are widely used--field calibration in natural soil profiles and laboratory calibration in prepared soil standards. Proponents of laboratory calibration favor it because accuracy is enhanced through the control of both soil material and moisture variation within the standard. Others favor field calibration because it reflects conditions as they exist in natural soil profiles.

4.31 - Field Calibration. Field calibration, as the name implies, is calibration in soils in place. All field calibration is based on the same principle and a suggested procedure is herein outlined.

Select a soil which is near to and representative of the study site. Level the soil surface and install an access tube. To insure rather homogeneous moisture conditions, measure the soil moisture at 2-3 inch depth intervals beginning at the surface. If abrupt changes in counting rate occur, indicating variable moisture conditions, a new location should be selected. Be sure to make shield counts both before and after moisture measurements. When a suitable location is selected, determine, according to the moisture content of the soil, the depth at which calibration observations are to be started. At shallow depths some neutrons escape into the air and in dry soils the "sphere of influence" is larger (about 30 inches) than in wet soils (about 18 inches). The sphere of influence or starting depth (soil containing 95 percent of thermal neutrons) can be computed by $12\sqrt[3]{\dfrac{100}{\%\text{ moisture by vol.}}}$ Beginning at the determined starting depth, make 5-minute counts at each 12-inch depth down to the lowest depth to be sampled. Measurements should not be made closer than four inches from the bottom of the access tube (see figure 4.34 for interface effects).

Remove the soil down to a point about 6 inches above the level of the most shallow neutron measurement. In a circle about 6 inches in radius around the access tube, collect a minimum of four volume samples of soil (figure 4.31). Remove the next three inches of soil and collect

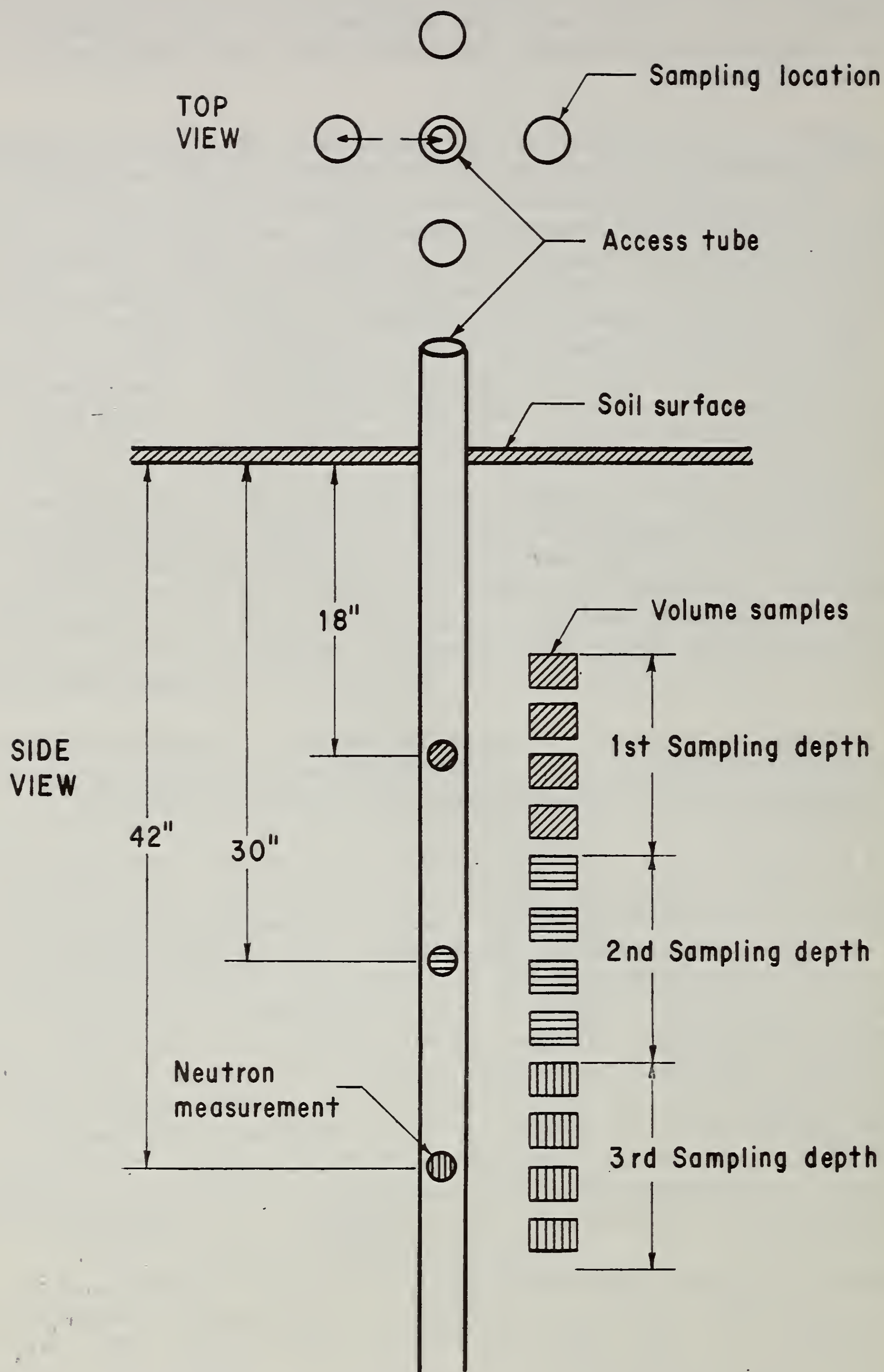


Figure 4.31. Diagram of a systematic method of collecting volume samples for field calibrating depth probes.

another set of four soil samples from a position somewhat turned radially from the original set. Thus, for each foot of soil you will have four samples of each 3-inch layer. Keep the samples separate for each one-foot depth and continue sampling until the desired depth is reached. Determine the moisture content of each sample by gravimetric methods (15) and obtain the mean moisture content for each foot of depth. The data should be examined for consistency and the mean moisture volume of each one-foot depth plotted over the count or count ratio made at the midpoint of each one-foot depth.

The described procedure is continued at other locations having different moisture levels until the slope and level of the curve is defined within the limits of precision desired. Compute the final prediction equation.

4.32 - Laboratory Calibration. The most practical medium for laboratory calibration is a well mixed natural soil of uniform moisture and density and of sufficiently large volume to contain the entire sphere of influence. Four-foot cube containers of wooden framework or metal are recommended (23).

Place 2-3 inches of loose, well mixed soil in the container and tamp to a uniform density. Add another 2-3 inches of soil and repeat the process until the container is filled. Install an access tube through the center of the soil block and survey with the probe the uniformity of moisture conditions at 2-3 inch intervals. With the probe at the mid-depth of soil, take a 5-minute count. Collect soil volume samples for moisture determination by gravimetric method, around the mid-depth probe sampling point as in field calibration. Repeat the process with other soil standards of different moisture contents and plot the data until the calibration curve is defined. Compute the prediction equation.

4.33 - Other Calibration Methods. If a calibrated probe is available, it can be used to calibrate a new probe. Measurements made at the same soil depth by both probes can be plotted into a calibration curve for the new probe.

Another method is to use a permanent set of standards which represent specific moisture volumes (23). Such standards can be made simply and relatively inexpensively from nonliquid hydrogenous material such as alum or paraffin. These standards can be used for recalibration of a probe, should this be necessary.

4.34 - Calibration of the Surface Foot. The surface foot is the weak area in the use of the neutron-scattering method. No completely satisfactory method of measuring moisture in the surface foot has been derived due to the escape of neutrons into the air as the soil-air interface is approached (figure 4.34). Sartz and Curtis (16) describe their procedure as follows:

> A Nuclear-Chicago neutron-scattering soil-moisture depth probe was field calibrated by taking meter readings at 2-inch intervals down to 2 feet and then taking gravimetric samples around the meter access tube. After the upper foot of soil had been removed in

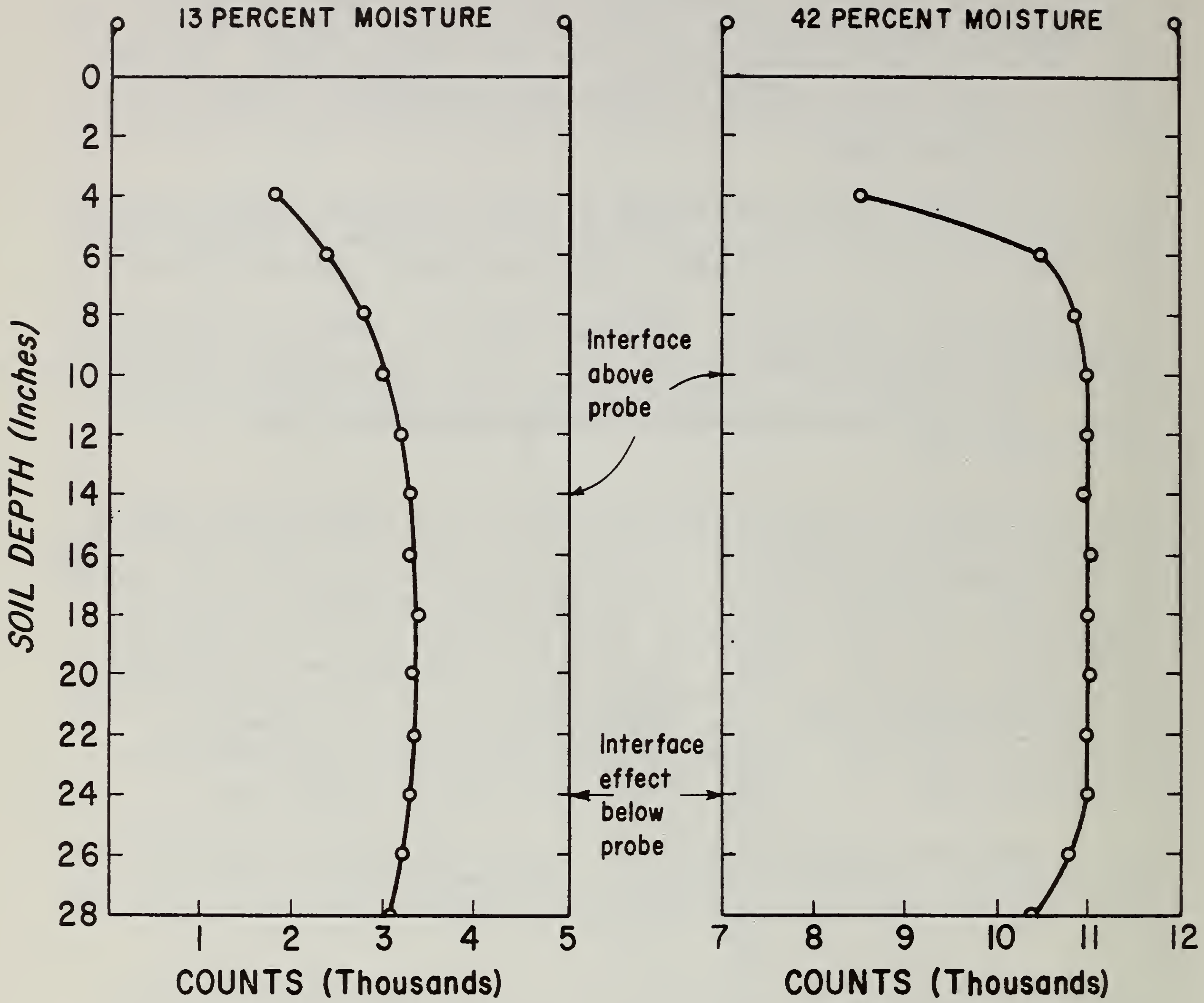


Figure 4.34. Soil-air interface effects in uniformly moist drums of soil is most pronounced above the detector tube and extends to greater depths in dry soil.

sampling, a second meter run was made in the lower foot of soil as a means of working out correction factors for shallow meter readings. The procedure was repeated three times. Moisture content ranged from 5 to 39 percent by volume.

It was found that the calibration curve furnished by the manufacturer gave an estimate of moisture content that was about 2 percent (by volume) higher at 10-percent moisture and 2 percent lower at 30-percent moisture. Differences increased beyond these extremes, and decreased to zero at 21 percent.

Correction factors for shallow readings were worked out that could be used to estimate moisture content in the surface foot of soil within the range of accuracy of the instrument. A single reading at 6 inches depth gave a satisfactory estimate. However, the method should be tested further in profiles where the moisture content varies more in the 0- to 6-inch layer.

4.35 - Calibration of Access Tubing. If access tubing different from that in the original calibration is used, the counts vs. moisture relationship may change, requiring correction of the calibration curve for the new tubing. This is accomplished by recording counts in one tube, removing that tube, inserting the second tube, and making a second count at the same point in the profile. These measurements should be made at a depth of 18 to 30 inches to eliminate soil-air interface effects. Data from several such comparisons made at different moisture levels will provide data to describe a calibration curve for the new access tubing.

## MEASUREMENT ERRORS AND THEIR REDUCTION

5.1 - Sources of Error. The objective of moisture measurement in a soil stratum is to determine the true moisture population. Since moisture content of soil varies from place to place and since the population can be determined only if the stratum is completely measured, the population is estimated by taking individual moisture samples at random. One problem of instrumenting studies is that, in addition to variation in the moisture population, one must also contend with the variation introduced by the instrument. Thus a field measurement contains errors arising from the variability of soil moisture from point to point and from variability of the instrument used to measure moisture.

Errors associated with field moisture estimates using nuclear methods include instrument error, timing error, positioning error, and location error. These errors can be calculated as a total, or preferably individually so that they can be examined for relative importance.

Instrument error originates from "noise" in electrical components and random sampling of the slow neutron density of the soil by the probe. The positioning error results from inability to position the probe at exactly the same point in the stratum each time samples are collected (use of a chain for positioning the probe will, for all practical purposes, eliminate this source of error). Timing error is the human or timer error which occurs when attempting to measure an exact time interval. These three sources of error are associated with instrumentation.

Location error reflects differences in moisture content from place to place in soil and is the largest source of error. Its size depends on the uniformity of slope, elevations, aspects, and soils which, when mixed, invariably increase the range of moisture conditions encountered. One study showed that moisture content increased one inch per foot of soil (8.3 percent by volume) with each 10-percent increase in clay content (figure 5.1) and if variation in clay content increased, the number of samples required to obtain a given standard error increased proportionately (4). Such site variations can mask treatment responses or may falsely indicate differences in moisture tension. Ideally, all extraneous sources of variation within the stratum should be minimized.

5.2 - Reduction of Error. Careful selection of the study area minimizes variation as does careful and efficient use of measurement equipment. Once the study area is selected, the only means of reducing the error of the moisture estimate is to obtain a better estimate of the population, usually by measuring more locations.

The magnitude and relative importance of sources of variation in moisture measurements can be determined if contribution of each source is known. A method of calculating the contribution of each source to total measured variance has been developed and will be published (7). This publication contains the mathematical development of formulas which are presented in summary form in this handbook.

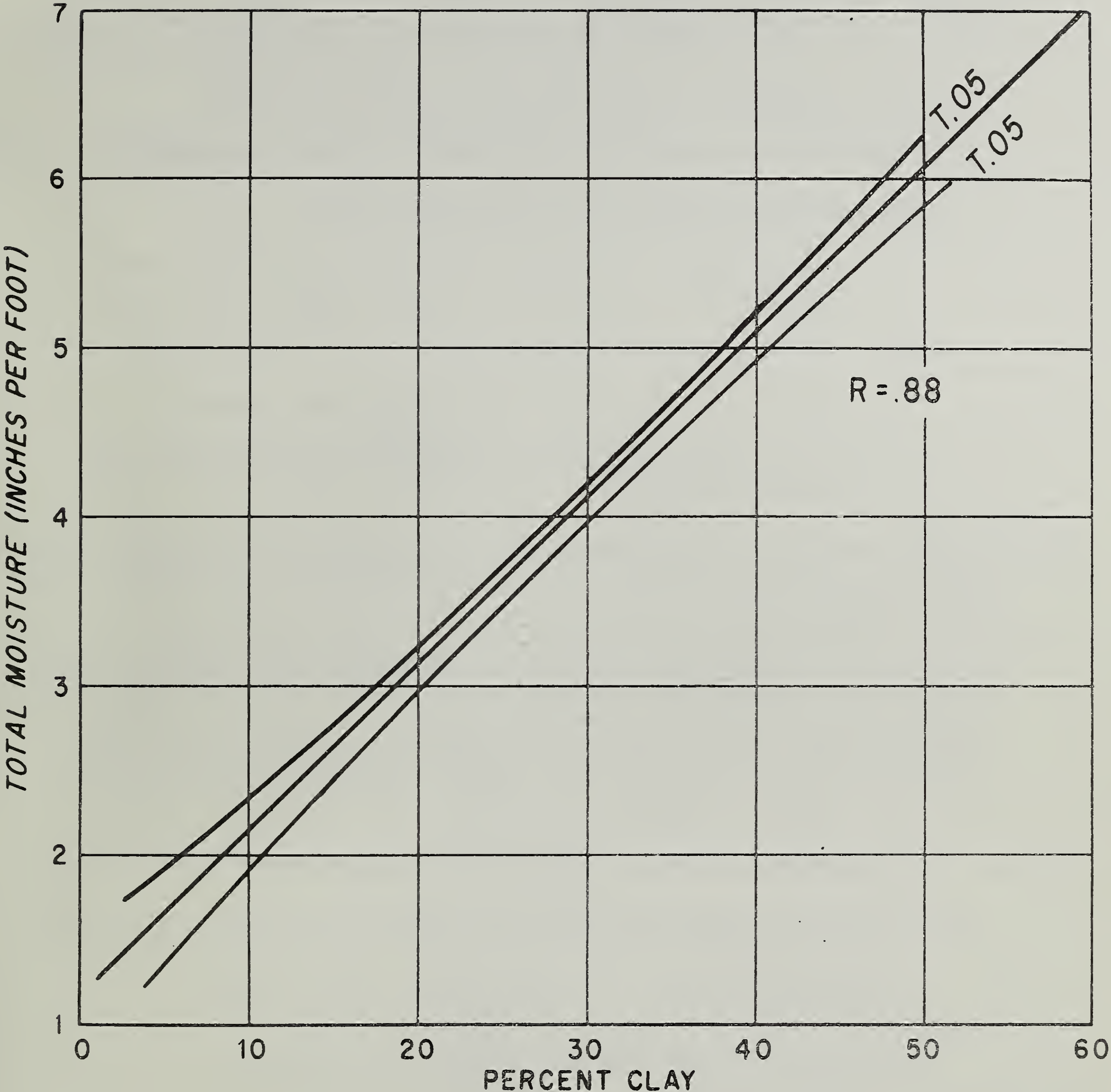


Figure 5.I --Relationship of total water to clay content.

The variance of moisture volumes determined from field measurements in a particular stratum is estimated by the formula:

Moisture Variance = [Location Variance] + [Instrument Variance] + [Timing Variance]
(Percent by Volume)

$$S_M^2 = \left[b^2 S_L^2\right] + \left[\frac{b^2 S_I^2}{T}\right] + \left[\frac{b^2 C^2 \; S_t^2}{T^2}\right]$$

where $S_M^2$ = variance of soil moisture in percent by volume.

$b$ = slope of the calibration curve in percent by volume per count.

$S_L^2$ = location variance in counts per minute.

$S_I^2$ = average number of counts per minute during the counting interval T.

$T$ = timing interval in minutes.

$S_t^2$ = variance of observing the desired timing interval.

$C$ = average number of counts per minute measured during the counting interval T.

In this problem the positioning error is assumed to be 0. If a positioning error occurs, it will be reflected in the location variance in the above formula.

A sample problem using actual field measurements illustrates how $S_M^2$ is calculated. Assume that b determined from the calibration curve regression equation is .004 percent volume per count, $S_t^2$ is .000003 (determined by comparing timer counts with 60-cycle current) and one-minute counts accumulated at 4 locations within a soil stratum are 13,400, 10,500, 9,400, and 10,800. Compute:

(1) Variance of the 4 counts x $b^2$ = 45.9067

(2) Instrument variance (mean of the 4 counts x $b^2/T$ = .1764

(3) Timing variance = .0058

(4) Location variance [(1)-(2)-(3)] = 45.7245

and:

$$S_M^2 = 45.7245 + .1764 + .0058$$

This example clearly shows that the largest contribution to total variance of moisture in the stratum is the location source which causes 99.5 percent of all variation. In comparison, instrument and timing sources are insignificant.

As stated earlier, moisture change with time is usually desired rather than moisture content particularly in study of moisture storage, evapotranspiration, drainage, and movement of water in the profile. Also, a stated advantage of in situ measurements is that the error of moisture observations is reduced by covariance which occurs when the same soil is remeasured. How important is the precision gain afforded by reduction of error by covariance? The formula for computing variance of a change in moisture between 2 sampling dates (7) provides a model for calculating the answer to this question.

$$\begin{array}{l}\text{Variance of a change in moisture (percent by volume)} = \left[\begin{array}{c}\text{Location variance}\\ \text{Date 1 + Date 2}\end{array}\right] - 2\left[\begin{array}{c}\text{Covariance be-}\\ \text{tween locations}\end{array}\right] + \\ \qquad \left[\begin{array}{c}\text{Instrument variance}\\ \text{Date 1 + Date 2}\end{array}\right] + \left[\begin{array}{c}\text{Timing variance}\\ \text{Date 1 + Date 2}\end{array}\right]\end{array}$$

$$S^2(M_1-M_2) = \left[b^2S^2_{L_1} + b^2S^2_{L_2}\right] - 2\left[b^2S^2_{L_1L_2}\right] + \left[\frac{b^2S^2_{I_1}}{T_1} + \frac{b^2S^2_{I_2}}{T_2}\right] + \left[\frac{b^2C_1^2\ S^2_{t_1}}{T_1^2}\right] + \left[\frac{b^2C_2^2\ S^2_{t_2}}{T_2^2}\right]$$

(Subscripts 1 and 2 indicate variance on first and second measurement dates.)

On the second measurement day, counts at the 4 locations were 13,600, 11,000, 9,800, and 11,800. Counting time, slope, and timing variance remain unchanged. The components of variance computed as before are as follows:

| | |
|---|---|
| Location variance | = 40.5021 |
| Instrument variance | = .1848 |
| Timing variance | = .0064 |

Location covariance (computed by standard statistical methods) is 42.3733.

Substituting into the variance of a moisture change formula we find:

$$\text{Variance of a change} = \left[\begin{array}{l}\text{Location}\\ \text{variance}\\ \text{Date 1 + Date 2}\end{array}\right] + \left[\begin{array}{l}\text{Instrument}\\ \text{variance}\\ \text{Date 1 + Date 2}\end{array}\right] + \left[\begin{array}{l}\text{Timing}\\ \text{variance}\\ \text{Date 1 + Date 2}\end{array}\right]$$

$$S^2(M_1-M_2) = 1.4800 + .3612 + .0122$$

Thus, analyzing data by moisture changes rather than total moisture content and accounting for covariance reduced the location contribution by about 96 percent. (The same total variance could have been obtained by determining

the change in moisture which occurred at each location and computing the variance of changes, thereby automatically including the covariance reduction.) The size of instrument and timing variance is now 20 percent of total variance.

These formulas are useful as models for comparing the sampling problem for the two methods of analysis and evaluating the merits of increasing the number of locations measured (n) vs. increasing the timing interval (T). Consider now the effect of varying the timing interval. The instrument variance is increased or decreased by T and the timing variance is increased or decreased by $T^2$. Both, however, are the least important sources of variance, and the largest source, the location component, remains unchanged. Clearly then, time could be more efficiently used to reduce the location contribution to total variance by measuring more locations (other factors remaining constant). Measuring more locations also reduces instrument and timing variance. For example, doubling timing interval reduces the total variance of a moisture change by only 10 percent because only instrument and timing variance are reduced, but doubling the number of locations measured reduces variance by 50 percent since all components are affected.

Figure 5.2 was constructed from the data presented previously to summarize the sampling problem for total moisture vs. change in moisture analyses. The figure assumes a constant sampling time of 5 minutes which is used in various combinations of n and T and illustrates the relationship existing between timing interval, number of locations measured and expected standard error of moisture content. It shows two important points concerning use of the neutron method for measuring moisture. First, the most precise method of comparing data is by moisture changes. Although moisture varies greatly in total content from point to point, soils gain or lose moisture rather uniformly. While moisture changes will always give the lowest error, the number of samples required to obtain a given error may differ for each stratum. In most cases fewer samples are required from deeper depths, but this must be determined locally since occasionally variability increases with depth. Second, little precision is gained by measuring more locations if the timing interval is reduced below 0.5 minute.

Time required to make field measurements depends on the timing interval used, the number of observations made per location, the number of locations measured, and the time required to travel between locations. A shorter time interval permits measurement of more locations but if measurement time is limited, all of the time savings cannot be reinvested in more locations because travel time is increased. Optimum timing intervals must be determined locally and involve economic as well as precision considerations.

In studies dealing with calibration or changes in moisture within a profile at one location, it is desirable to use long timing intervals. Where only one location is sampled, precision is increased only by taking longer counts. Those portions of the formula relating to random counting and timing variance are useful in evaluating effects of increasing timing interval on reducing instrumentation error.

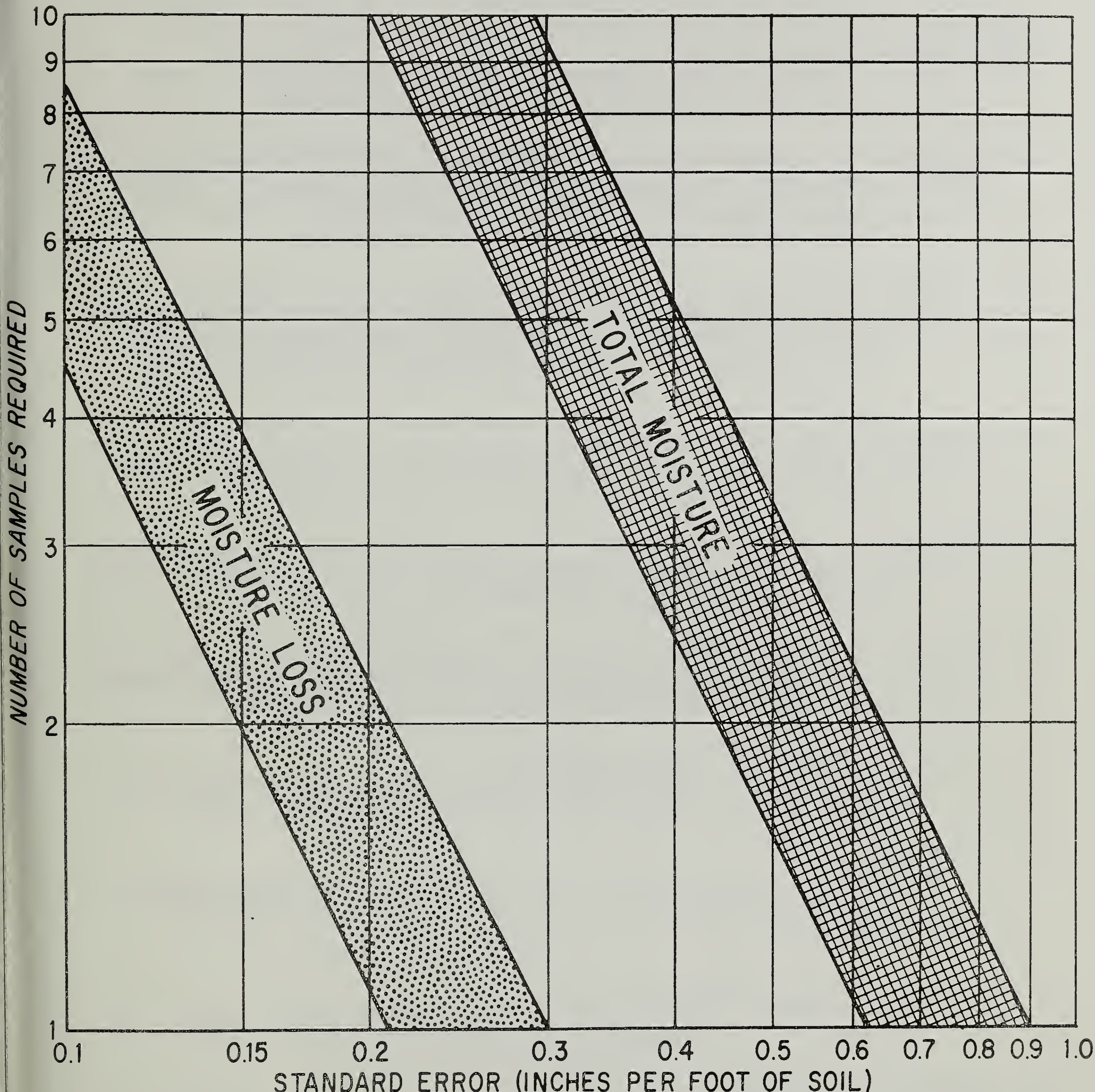


Figure 5.2--Number of samples required to hold the standard error of total moisture and moisture loss to specific amounts. Upper and lower limits represent ranges in clay content of 40 and 20 percent respectively. The curve is valid only to a depth of 5 feet.

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